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Which Hybrid Powertrain would be Suitable for your Vehicle to Reduce CO2 emissions?

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Abstract

Evaluation of powertrain configurations for performance, emission and efficiency benefits using computer simulation tools has become part of the standard vehicle development procedure. The wide variety of available powertrain options along with the various hybrid systems necessitate AVL to simulate and evaluate these in order to obtain the configuration with the best benefit potential. AVL's vehicle systems and driveline analysis tool CRUISE can be used to perform these simulations and analysis in a user friendly and efficient manner. CRUISE has a unique layering feature used to build up a vehicle model in several sub-systems (layers). The various components in the vehicle model are grouped together to form different sub-system layers. The conventional components of the baseline vehicle are grouped together to form the conventional layers, upon which the additional hybrid system components are added to form the hybrid layers. These various layers can be activated or deactivated as necessary, allowing users to simulate the vehicle for fuel economy, performance and emissions for different powertrain hybrid configurations in the same vehicle model. This paper evaluates and compares the CO2 reduction potential for different hybridization options for a super-mini class vehicle and also lays out the relative cost of implementing these different hybrid powertrains. The simulation results combined with the cost benefit analysis allows automotive OEMs to choose the specific hybrid technologies as per their fleet requirements.

Keywords: HEV (hybrid electric vehicle), modeling, simulation, emissions

1 Introduction

Vehicular emissions are increasingly stringent and there is a big effort from the automobile manufacturers to design and develop new vehicle technologies in order to achieve the target emission requirements. It is vital to know the technological options available to reduce emissions, especially CO2. AVL is evaluating and researching current and future powertrain options including hybrid vehicle systems in order to help the OEMs meet these emission reductions. AVL's vehicle and system simulation tool CRUISE is one of the various tools being used for powertrain evaluation and comparison.

AVL CRUISE is used in drive train development to calculate and optimize fuel consumption, emissions, performance, transmission ratios, etc. The modular structure of CRUISE permits modeling and simulation of all existing and future vehicle powertrain concepts and a parametric evaluation of the various components can be performed.

The aim of the modeling and simulation analysis is to analyze the potential fuel economy and emission benefits possible from different hybrid powertrain architectures. A European super-mini class segment passenger vehicle with a 1.6 liter gasoline engine was modeled using CRUISE and constituted the base reference model. The vehicle was then hybridized progressively to constitute the various hybrid architectures.

The paper reviews the different hybrid configurations, describes the basic control strategy implemented and the associated vehicle implementation costs.

2 Introduction to the simulation model

The base model is a current market super-mini class vehicle with a 1.6 turbo charged gasoline engine and a six speed manual transmission. The model was built using CRUISE and the fuel economy and emission data was validated by comparing it to the official manufacturer numbers. The model is shown below in figure 1.

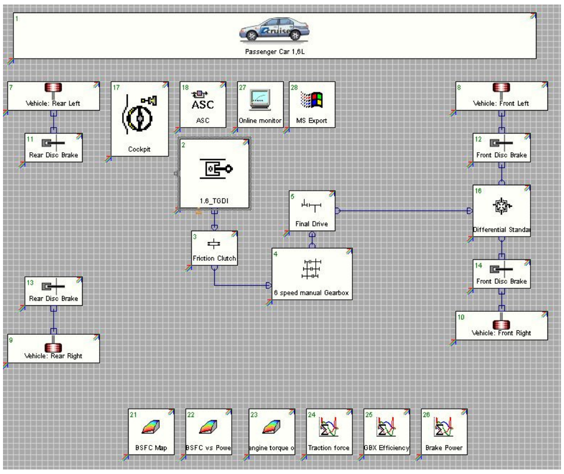

Figure 1: Base Vehicle Model

In AVL CRUISE it is possible to group components and their connections into sub-systems. For example, using four sub-systems, three kinds of Powertrain architectures can be defined as shown in the figure 2.

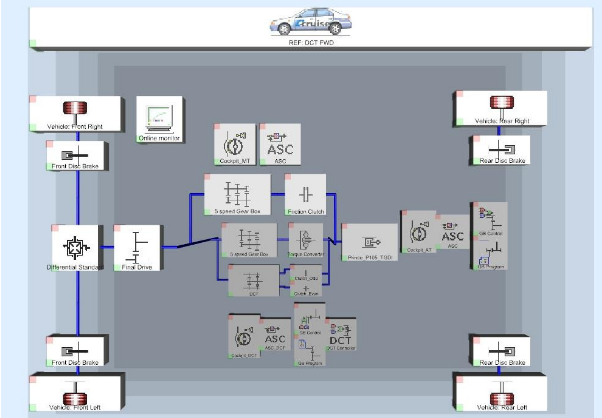

Figure 2: CRUISE “Layering” Feature

In figure 2 common drive train components like chassis, tires, brakes, etc which are common for most of powertrain configurations have been grouped together into one sub-system. The different powertrain options like engines, transmissions have been added to a different layer. Various powertrain configurations can be generated by activating a combination of these layers. Similar activation and deactivation of the hybrid sub-system layers produces different hybrid powertrain configurations. A wide variety of hybrid vehicle configurations can be modeled and simulated including series, parallel, power split etc in a single model.

The vehicle modeling techniques used in the fuel economy studies can be divided into two categories according to the direction of the power flow calculation. One is backward, which calculates the required power from the wheel to the engine, and the other is forward, which calculates the power from the engine to the wheel. The main difference is that the forward simulation model requires a driver model and there is an error in the vehicle speed between the reference speed and the real simulation result. CRUISE features both forward and backward simulation solvers. For the fuel economy study, the backward simulation can provide faster and more accurate results. A quasi-static backward simulation is useful for initial component sizing, design of the controller. However, detailed dynamics of the powertrain including sensors and actuators and a driver model are not included. Going toward the implementation stage, the controller should be verified using a dynamic forward model which is a more realistic environment.

2.1 CRUISE Hybrid Models

Baseline simulation models were initially developed for the super-mini class conventional vehicle followed by the hybridized versions. The hybrid vehicle component specifications were then selected based on the methodology used by Cho and Vaughan [1] for US SUV's in their study.

The following hybrid architectures were modeled and analyzed:

- Belt Starter Generator (BSG)
- Crankshaft Starter Generator (CSG)
- Through the Road (TTR)
- Power Split (PS)
- Series

The CRUISE layering feature has been used to incorporate the additional hybrid components allowing for easier model management and faster model build time.

BSG system shown in figure 3 is the first level of hybridization and is the simplest of the hybrid architectures. The BSG system adds the following functionalities to the base vehicle:

- Engine start-stop
- Limited regenerative braking

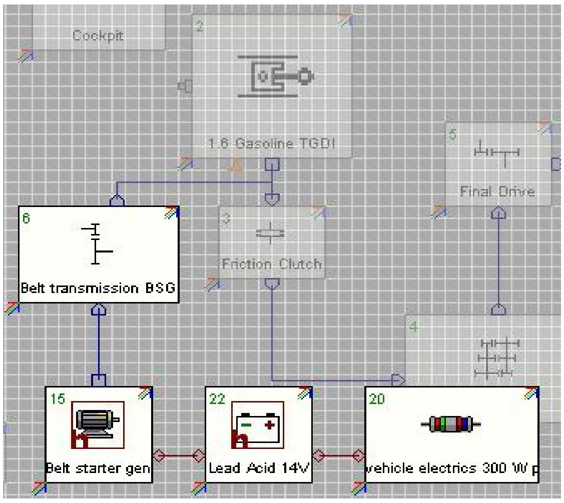

Figure 3: BSG Hybrid Sub-System

In CSG systems the crank starter generator is installed between the engine and the transmission. The rotor of the electric machine is connected to the crankshaft and the stator is mounted to the transmission bell housing or a separate intervening housing. The CSG system adds the following functionalities to the base vehicle:

- Engine start-stop
- Regenerative braking
- Acceleration assist/boost

The CSG sub-system implemented in CRUISE is shown in figure 4.

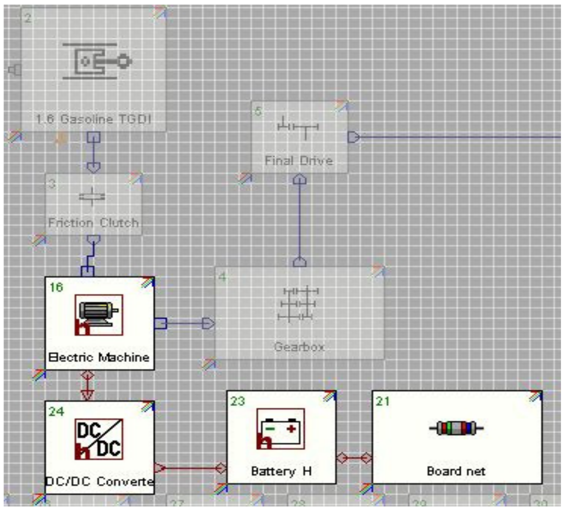

Figure 4: CSG Hybrid Sub-System

A parallel TTR system separates the electric drivetrain from the engine, simplifying the mechanical connections while adding all electric drive functionality. The TTR sub-system is shown in figure 5. The TTR system adds the following functionalities to the base vehicle:

- Engine start-stop
- Regenerative braking
- Acceleration assist/boost
- All electric driving capability
- Limited all wheel drive capability

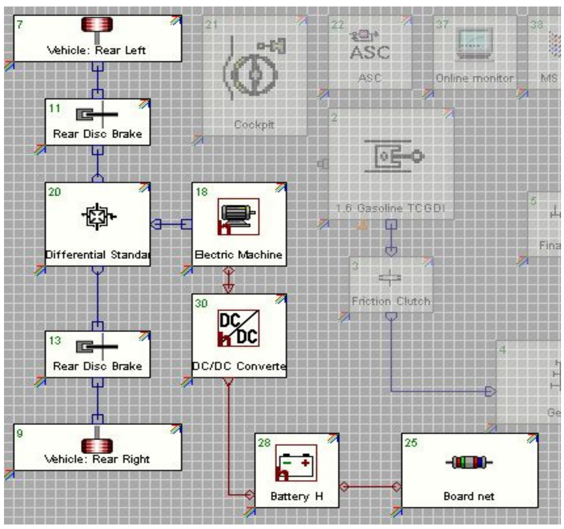

Figure 5: TTR Hybrid Sub-System

A Power Split hybrid system is a full hybrid system and requires a hybrid control system of the highest complexity. The conventional gearbox of the base vehicle is replaced with a planetary gear box, this allows for full hybrid functionality. The PS hybrid architecture shown in figure 6 adds the following functionalities to the base vehicle:

- Engine start-stop
- Regenerative braking
- Acceleration assist/boost
- All electric driving capability
- Electric all wheel drive option possible (not used here)

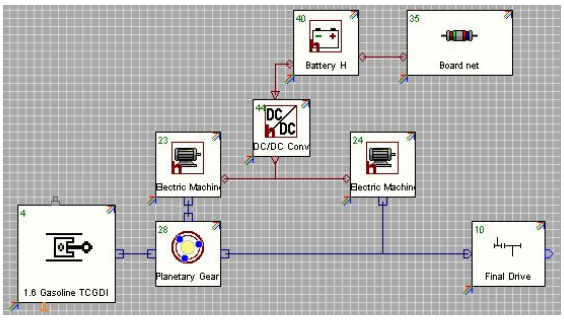

Figure 6: PS Hybrid Sub-System

Series hybrid operation is achieved by using the engine to drive the secondary electric machine (generator) while the primary electric machine propels the vehicle. In series hybrid systems, the engine is usually downsized and the primary electric machine is full sized to meet the vehicle performance requirements. This allows the engine to run at its optimum operational point. The SH sub-system is shown in figure 7. The series hybrid architecture adds the following functionalities to the base vehicle:

- Engine start-stop
- Regenerative braking
- Acceleration assist/boost
- All electric driving capability

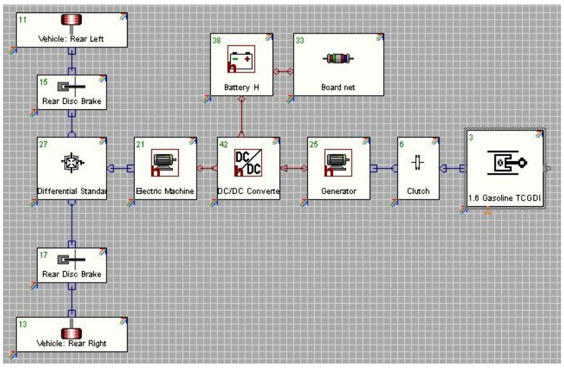

Figure 7: Series Hybrid Sub-System

The functionalities of the different hybrid systems are summarized in figure 8.

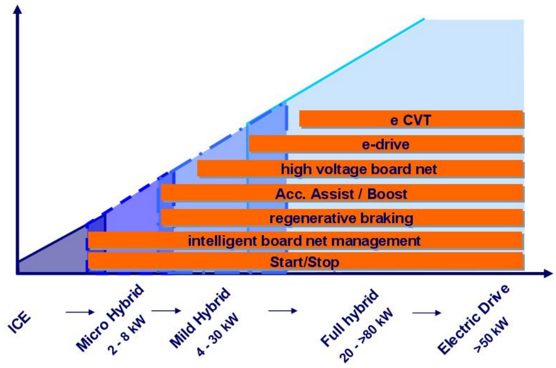

Figure 8: Hybrid Powertrain Functionalities

3 Hybrid Control Strategy Overview

Hybrid control strategy especially the energy management and blending functions are unique and have to be developed specifically for each application. Each powertrain architecture brings with it the ability to perform certain hybrid functions. Generally speaking, the complexity of the controller goes up with the increase of the degree of hybridization and the functionality of the powertrain architecture. This section deals with a general overview of some of the features of the control systems developed for CRUISE vehicle models.

A general methodology for estimating the potential fuel economy for a specific hybrid drivetrain is given by the equation below:

Fuel consumption of a hybrid =
*fc_basis + fc_wt*extra_weight – idle_fc -*
*(fc_basis+fc_wt*extra_weight)**
*ratio_driving_energy*ratio_recup_energy* (1)

Where,

- fc_basis is the fuel consumption of base non hybrid vehicle
- fc_wt is the additional fuel consumption constant due to added weight (empirical)
- extra_weight is the additional weight of hybrid components
- idle_fc is the fuel consumed during idling
- ratio_driving_energy = ratio of driving energy of non hybrid vehicle to driving energy of hybrid vehicle
- ratio_recup_energy = ratio of effective recuperation energy to total energy produced by engine

The above equation allows for a quick estimation to find out the potential gains for the different hybrid configurations.

The power management subsystem in CRUISE plays a critical role in fuel efficiency and emissions.

The subsystem has been broadly divided into three main blocks:

- The high level operational modes of the vehicle are managed by the State machine logic module in the controller
- A high level energy control block that controls and computes the necessary and available energy from the engine, traction motor and the energy storage system as per the driver demand
- An engine controller that ensures which ensures the engine is the primary motive power in the BSG, CSG ,TTR hybrids and maintaining the engine at the lowest brake specific fuel consumption (BSFC) region for longer periods in PS and series hybrids

One of the key control strategies used in the control algorithm is the Load Point Shifting (LPS) event algorithm.

3.1 Load Point Shifting Events

At constant engine speed, the engine torque is increased to operate the engine in an area of BSFC map where more electrical energy can be generated. Thus some extra fuel will be consumed due to LPS events, but it will also contribute to more recuperative energy. This section explains the LPS event strategy in more detail.

When a vehicle is cruising at constant velocity, it is found that the torque generated by the engine is quite low and the BSFC is quite high.

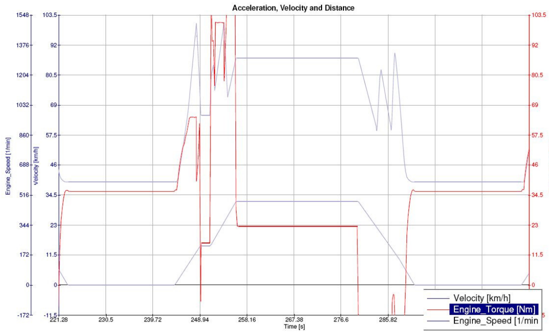

Figure 9: CRUISE Drive Trace

For example, it can be seen from the CRUISE simulation figure 9, in the time interval 258s to 280s,
Vehicle speed = 32 kmph
Engine Speed = 1322 rpm
Torque = 16 Nm
Power = 2.2 kW
BSFC=0.56 kg/kWh

This operational point is assumed as point A as shown in figure 11. A map of Torque vs. Engine speed is then defined assuming it is operating at the best possible BSFC value as shown in figure 10.

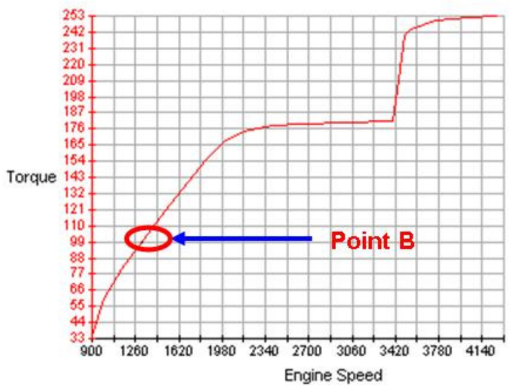

Figure 10: Engine Speed - Torque for Best BSFC

The ideal engine torque for an engine speed of 1322 is found to be around 99 Nm from figure 10. This operational point is assumed as point B. BSFC at point B is determined to be 0.26 kg/kWh while at point A it is 0.56 kg/kWh from the specific consumption values in figure 11.

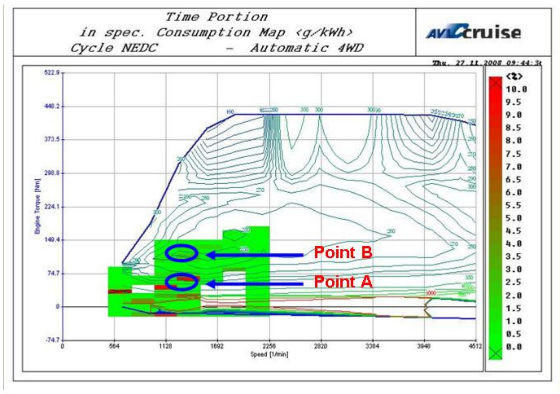

Figure 11: Load Point Shifting

Shifting the load point from point A to point B increases the torque by almost 6 times. If the vehicle has an electrical generator which is capable of absorbing this torque, it can potentially generate electrical energy when the vehicle is cruising at constant speeds recharging the battery while providing the necessary vehicle driver demand.

Fuel consumed by the engine is directly proportional to the product of BSFC and torque produced. The ratio of fuel consumed at point B to fuel consumed at point A is given by

(Torque_B*BSFC_B)/(Torque_A*BSFC_A) (2)
= (99*0.26) / (16*0.56)
= 2.87
The ratio of energy generated by engine at Point B to Point A= 99/16 = 6.18

Thus, by consuming 2.87 times more fuel, the engine is now generating 6.18 times more energy, which can be harnessed by electric generator and battery. This is the basic concept behind an LPS event. To ensure that the energy gained is sufficient to offset the extra fuel consumed, a criterion is used to define this event. I.e. the ratio of BSFC at point B and point A should be greater than a set value. If this ratio is too high, then occurrences of LPS event would be minimal. If this ratio is too low, it is possible that the extra energy may not offset the additional fuel consumed. This set value is defined based on the vehicle operational characteristics and the drive cycle demands.

The above control strategy is called the LPS-1 algorithm and is being implemented in the CSG and TTR hybrid CRUISE models.

There is a second LPS strategy for full hybrid configurations like series and power split defined as LPS-2 algorithm. It is found that engine operates at low BSFC values for mid power values as shown in figure 12.

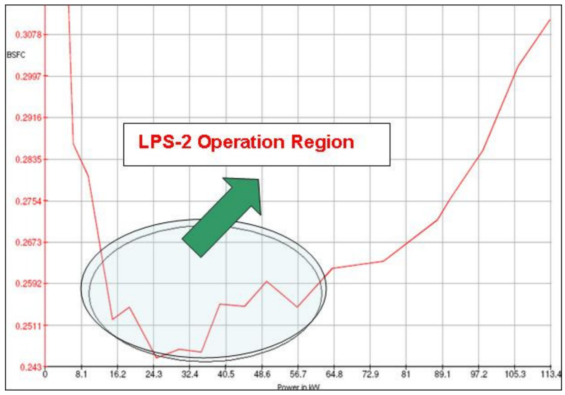

Figure 12: LPS-2 Defined Operational Region

In a vehicle with a high degree of hybridization like a power split or series, the electric machine can act as a generator in the low power region and as a motor in the high power region, ensuring that the engine operates in low BSFC range for a substantial amount of the drive cycle time. An LPS-2 event is defined in CRUISE models when the actual BSFC is less than 1.1 times minimum specific BSFC value. This value has been defined for the NEDC cycle and needs to be calibrated for the different drive cycle.

The LPS-2 control strategy is being implemented in the PS and Series hybrid CRUISE models.

4 CRUISE Simulation Results

The CRUISE vehicle models were simulated and optimized for the New European Driving Cycle (NEDC) which lasts for 1180 seconds and consists of two parts. The first part ,780s long is the Urban Driving Cycle (UDC) followed by the Extra Urban Driving Cycle (EUDC) which is 400 seconds. The profile of the drive cycle is shown in figure 13.

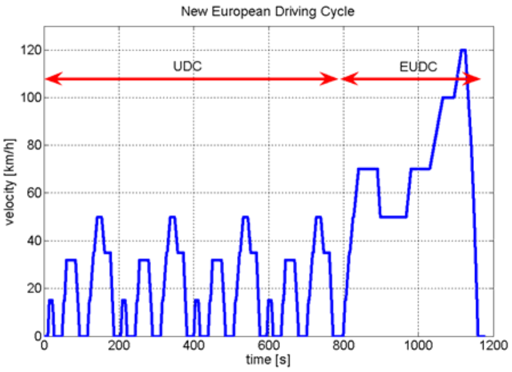

Figure 13: New European Drive Cycle

The CRUISE fuel economy and CO2 simulation results for the various hybrid architectures analyzed for the NEDC cycle are shown in table 1 and CO2 emission results in table 2.

Table 1: CRUISE Fuel Consumption Results

Vehicle Architecture	Fuel Consumption	
	L/100km	%
Baseline	6.62	100.00
BSG	6.43	97.11
CSG	6.03	90.96
TTR	5.58	84.21
PS	5.16	77.92
SH	5.53	83.53

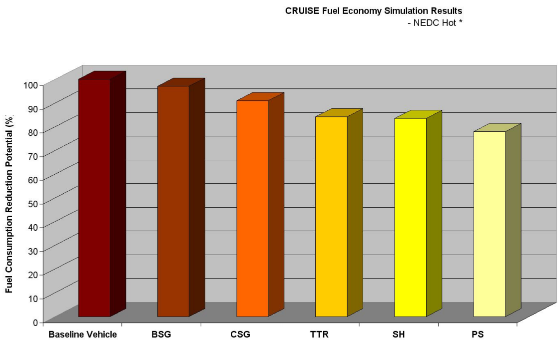

Figure 14: Fuel Consumption Reduction Potential (%)

Table 2: CRUISE CO2 Emission Results

Vehicle Architecture	CO2-Emissions	
	g/km	%
Baseline	157.66	100.00
BSG	153.11	97.11
CSG	143.41	90.96
TTR	132.77	84.21
PS	122.85	77.92
SH	131.69	83.53

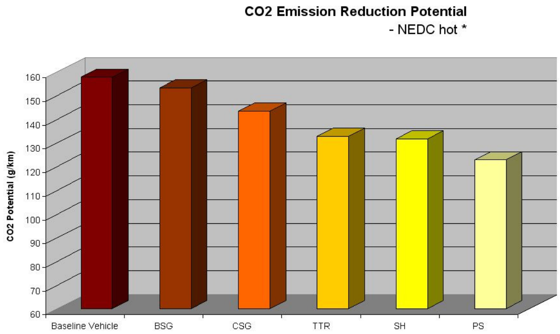

Figure 15: CO2 Emission Reduction Potential

The results show that the reduction potential increases with increasing vehicle hybridization. Series hybrid shows a higher fuel consumption value than the power split due to insufficient engine downsizing and optimization of the control strategy. The control strategies implemented in the CRUISE models in this study need to be further optimized to obtain the maximum fuel and emissions savings.

5 Hybrid Powertrain Implementation Costs

There are still different opinions as to whether the HEV is worth introducing or not, and most of these arguments revolve around the relative fuel benefits versus the incremental cost. In general, the potential fuel bill saving is same or less than the optional cost of hybridization at this moment. Hybridization ratio is a good measure to compare the costs of different hybrid architectures. It can be defined as the ratio of peak electric power to the whole vehicle powertrain power. Figure 16 shows the degree of hybridization and energy blend of components.

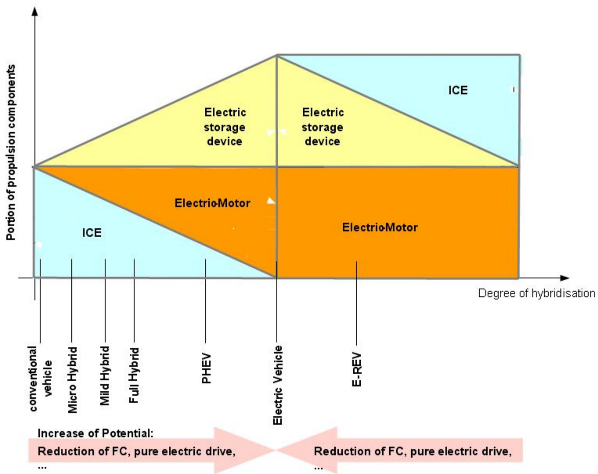

Figure 16: Degree of Hybridization and Functionalities

However, continuing technological improvement is cutting the cost of advanced powertrain and its components. On the contrary, oil price is increasing and not likely to come down in the long term. Moreover, limited reserve of fossil fuel and global warming by greenhouse gas are making governments initiate various incentive programs such as tax return, redemption of congestion charges, and free parking. Therefore, genuine competition in alternative powertrain field is just the beginning. AVL has a long experience of hybrid vehicle and system development and has successfully completed numerous projects for various automotive OEMs. Figure 17 shows the approximate relative costs for different hybrid systems to obtain the required CO2 emission reductions.

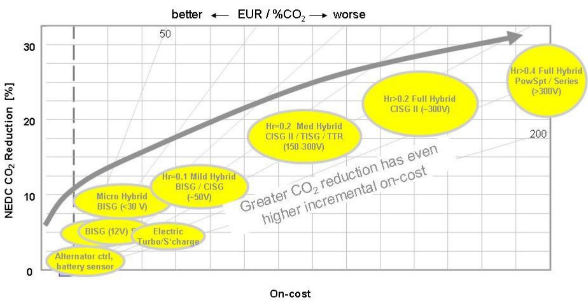

Figure 17: Cost per % CO2 Reduction Potential for Different Technologies

The different automotive manufacturers choose to implement different technologies based on factors like vehicle class, target market, fleet emission and fuel economy regulations etc. AVL's project delivery experience and its hybrid development tools can guide the customer to make the right choice.

6 Conclusion

The usage of computer modeling and simulation tools in the age of increasingly stringent emissions and fuel economy regulations is necessary and aids in cutting down the costs and development process of increasingly advanced vehicle powertrains. AVL CRUISE is a versatile and modular tool which can help automotive manufacturers and system developers. CRUISE was successfully used to analyze the fuel consumption and CO2 emissions reduction potential for European super-mini class vehicle for five different hybrid architectures. A basic control system was implemented for these different hybrid powertrains which needs to be further optimized using tools like dynamic programming to obtain the full benefit potential of the hybrid configurations. The approximate relative cost of implementing the hybrid powertrains in real world projects based on AVL Powertrain UK's project delivery experience has also been detailed in this paper.

AVL believes that the electrification of the powertrain will continue at a growing pace and this will provide cleaner and better driving vehicles. On the other hand although this paper focused solely on hybridization it is by no means the only way to reduce CO2 emissions. There are many other opportunities like vehicle weight reduction, alternative fuels and fuel cell technologies which can provide significant fuel economy benefits, for which AVL is committed to research and investigate.

Acknowledgments

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